IONOSPHERIC AND THERMOSPHERIC WEATHER: SIMULATIONS AND APPLICATIONS

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LONG-TERM GOAL

The long-term goal of this research is to elucidate the physics associated with the creation, transport, and decay of mesoscale ionospheric density structures and to determine their effect on Naval systems. Of particular interest are propagating plasma patches, density structures associated with sun-aligned polar cap arcs, and density structures created during geomagnetic storms and substorms.

SCIENTIFIC OBJECTIVES

Mesoscale plasma density structures are prevalent in the ionosphere at all latitudes. When the interplanetary magnetic field (IMF) turns southward, plasma patches form on the dayside of the high latitude ionosphere and then propagate in an antisunward direction across the polar cap. When the IMF turns northward, sun-aligned arcs appear in the polar cap. Also, during geomagnetic storms and substorms, the enhanced convection and localized particle precipitation leads to ionospheric density structures. Associated with plasma density structures are enhanced levels of scintillation. One of our objectives is to determine the exact mechanisms responsible for creating plasma structures under different seasonal, solar cycle, and geomagnetic activity conditions. Another objective is to determine the lifetimes and transport characteristics of the various plasma structures. A third objective is to determine the extent to which plasma patches can affect the thermosphere. Our final objective is to determine the effect of plasma structures and irregularities on Naval systems.

APPROACH

Our approach is to use time-dependent, high-resolution, multi-species models of the global ionosphere and thermosphere to simulate the effects of geomagnetic storms and substorms and to model density structures for a wide range of geophysical conditions. The simulated ionospheres and thermospheres can then be used to determine the effects that density structures and geomagnetic storms have on operational systems, such as HF communications, radar altimetry, GPS signals used for navigation, and the interpretation of emissions measured by the Navy's SSUSI and SSULI instruments, which will be flown on DMSP satellites.

WORK COMPLETED

During the last year, several studies were completed with regard to elucidating the causes of ionospheric and thermospheric weather and several other studies are still ongoing. The completed studies involved simulations of the effects on the ionosphere of geomagnetic storms, substorms, and regular variations in the B_z and B_y components of the IMF. Simulations were also conducted

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to study the effect on the thermosphere of a series of propagating plasma patches, which are frequently observed in the high-latitude ionosphere. A cumulative list of our papers is given in the Reference section.

RESULTS

In the paragraphs that follow, we highlight two of our recent studies that produced significant results. The highlights are:

1. *Ionospheric Response to Changing IMF*:
   The high-latitude ionosphere is known to vary markedly with the direction of the interplanetary magnetic field. When the IMF is southward ($B_z<0$), plasma convection exhibits a 2-cell pattern with antisunward flow in the polar cap and return flow equatorward of the auroral oval. The two cells can be symmetric or asymmetric, with enhanced flow in either the dawn or dusk sectors, depending on the IMF B_y component. For northward IMF ($B_z>0$), sunward flow can occur in the polar cap, and this feature has been explained in terms of a severely distorted 2-cell configuration as well as by a multi-cell pattern. Recently, Weimer (1995), using DE-2 satellite data, constructed an IMF-dependent empirical model that yields convection patterns for a full range of B_z and B_y. These patterns are in substantial agreement with those deduced using the superDARN radar system (Ruohoniemi and Greenwald, 1996). Since reasonable convection patterns are now available for the full range of IMF values, we simulated the ionospheric response to these patterns in order to elucidate the evolution of large-scale ionospheric features as the IMF varies from southward to northward. Both summer and winter conditions were considered for moderate solar activity. For northward IMF, unique ionospheric features are predicted to occur. Specifically, in winter, localized ionospheric holes can develop in the polar cap in association with the reverse convection cells. The plasma density in the localized hole can be as much as a factor of ten lower than that in the surrounding region. Also, the plasma density in the main (or mid-latitude) trough, which is situated just equatorward of the nocturnal auroral oval, is much deeper for northward IMF than for southward IMF. These localized regions of plasma depletion will have a major impact on HF communications, OTH radars, and TECs obtained from slant path GPS signals; and

2. *Thermospheric Perturbations Induced by High-Latitude Plasma Structures*:
   Mesoscale plasma structures are common in the ionosphere at all latitudes (e.g., Schunk and Sojka, 1996). In the polar cap, two prominent ionospheric structures are propagating plasma patches and sun-aligned auroral arcs. Polar cap patches are regions of enhanced ionization that appear when the interplanetary magnetic field (IMF) is southward. They are created either in the dayside cusp or equatorward of the cusp in the sunlit hemisphere. Once formed, they convect in an antisunward direction across the dark polar cap at speeds of from 100 m/s to about 2 km/s. The size of the plasma patch varies from about 100 to 1000 km, and its density relative to the background density varies from a few percent to a factor of 100. Sun-aligned polar cap arcs, on the other hand, cause regions of enhanced ionization that frequently appear when the IMF is near zero or northward. They are typically associated with a shear in the convection electric field, which leads to electron precipitation and plasma density enhancements that can be up to 10 times background plasma densities. The sun-aligned arcs are about 100-300 km in width and 1000 km in length.

With regard to the thermosphere, propagating plasma patches act to drive the thermosphere, because the plasma patches typically move faster than the neutral atmosphere. Sun-aligned arcs, on the other hand, offer a resistance to the basically antisunward neutral gas flow. However, a determination of their quantitative effect requires a detailed numerical calculation. To this end, we constructed a fully global, time-dependent model of the thermosphere that has a sufficient spatial resolution in the polar cap to account for propagating plasma patches and sun-aligned arcs. The model is based on a numerical solution of the continuity, momentum, and energy equations for the neutral gas, and the equations are solved in a coordinate system that is fixed to the rotating Earth using a multi-dimensional flux-corrected-transport (FCT) technique. The horizontal resolution in the polar cap is 50 km, and there are 25 layers in the vertical direction that cover altitudes between 97 and 500 km.

In the plasma patch simulations, diurnally reproducible neutral densities, temperatures, and winds were initially calculated for quiet geomagnetic activity, June solstice, and solar minimum and maximum conditions. Subsequently, at a selected time, a series of plasma patches is introduced in the vicinity of the dayside cusp at a time interval that is consistent with measurements. The patches then convect, one after the other, in an antisunward direction across the polar cap. The model predicts that the propagating plasma patches act as collisional snowplows, creating a build-up of neutrals at the fronts of the patches and a neutral depletion both in and behind the plasma patches. The neutral disturbances that are induced by, and moves along with, the plasma patches are also characterized by temperature enhancements, increased wind speeds, neutral gas upwellings, and O/N_2 composition changes. At later times, the patch induced disturbances spread out and overlap each other, which creates a disturbed region that nearly encompasses the entire polar cap and nocturnal auroral zone. These plasma patch simulations clearly indicate that the thermosphere is much more structured than previously thought.

IMPACT/APPLICATION

Sharp horizontal gradients, deep ionization holes, extended electron density troughs, and ion composition changes have been predicted to occur when the IMF changes direction and when storms and substorms occur. These plasma density features could have a significant impact on Naval systems and operations that involve radar altimetry, navigation, HF communications, and ionospheric corrections to single-frequency GPS receivers. Also, the non-uniform neutral atmospheric densities predicted by our thermospheric model could affect the interpretation of Navy remote sensing instruments that will be flown on future DMSP satellites.

RELATED PROJECTS

The ionospheric simulations we have conducted are being used by Joe Grebowsky, who is at NASA's Goddard Space Flight Center. Specifically, he is comparing our model predictions with NASA satellite (AE and DE) data in an effort to validate our predictions. Our simulation results are also being used in a community-wide validation effort called PRIMO, which is funded primarily by the NSF and the Air Force.

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